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EVALUATION OF A SEISMIC DAMAGE PARAMETER

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SUMMARY

Several parameters have been proposed in the literature for the evaluation of seismic damage. However, in most cases the correlation between results obtained using these parameters and observed damage in structures has not been satisfactory. A parameter for measuring seismic damage previously proposed by the first author is used in this study to analyse a set of 15 accelerograms recorded in 11 earthquakes experienced in different countries. Results using this parameter are compared to global building damage observed during these earthquakes. The use of the parameter proposed here yields results which are consistent with building damage observed in the earthquakes studied. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: damage parameters; earthquake; non-linear response

INTRODUCTION

There is an urgent need to improve seismic design and construction procedures, to develop better methods for assessing the seismic vulnerability of existing structures and to define rational retrofitting strategies and techniques. An important step towards reaching these goals is to define an adequate measure of the capacity of earthquakes to damage a specific type of structures, which in the following is referred as a damage parameter. Several parameters have been proposed in the literature for such a measure. However, in most cases the correlation between results obtained using these parameters and observed seismic damage in structures has not been satisfactory.

In the last decade several important accelerograms have been recorded during different earthquakes and observed structural and non-structural damage has been well documented. This information gives an unique opportunity to explore the possibility of finding a reliable parameter for measuring seismic damage. Such a parameter should consider not only typical characteristics of earthquake ground motions but also characteristics representative of structures.

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A damage parameter previously proposed by the first author is used in this study. It uses a non-dimensional hysteretic energy, an acceptable roof drift ratio and the maximum roof drift ratio of a building during an earthquake excitation. A set of 15 accelerograms recorded during several earthquakes experienced in different countries and having different levels of intensity is analysed. Results using the proposed parameter for the selected earthquakes are compared to the observed global building damage.

EARTHQUAKE GROUND MOTIONS AND OBSERVED BUILDING BEHAVIOR

In this study, 15 accelerograms recorded in 11 earthquakes experienced in different countries and having different levels of intensity are analysed. The earthquakes studied are (in chronological order): California, USA, 1940; Peru, 1974; Rumania, 1977; Japan, 1978; Chile, 1985; Mexico, 1985; San Salvador, 1986; Mexico, 1989; Loma Prieta, USA, 1989; Northridge, USA, 1994; and Japan, 1995.

Table I shows some typical characteristics of the earthquake ground motions that have been used, which include magnitude M_s, Modified Mercalli Intensity, MMI, epicentral distance, soil type at the recording site, peak ground acceleration, A_{max}, and the abbreviations used for the records selected.

Building behaviour observed during the earthquakes studied is well documented in the literature. According to a review of this information and considering the MMI values shown in Table I, the most destructive earthquakes were the ones experienced in Mexico City (1985), Northridge, USA (1994) and Kobe, Japan (1995). The review also shows that only a few cases of some non-structural damage were observed in earthquakes related to the RM, LM and VI records.

APPROXIMATE LATERAL DISPLACEMENT ANALYSIS OF STRUCTURES

It is of interest to evaluate the lateral displacements of structures since they are closely related to seismic damage. A simple approach is chosen here for the evaluation of lateral displacements, which uses SDOF systems to analyse global displacements of multistorey buildings. A constant deflected shape is assumed for the seismic analysis of multistorey buildings and the roof displacement, δ, is selected as a response parameter of an equivalent SDOF system.[1–3]

The maximum roof drift ratio in a multistorey building, D_{rm}, is defined as

$$D_{rm} = \frac{\delta_m}{H} \tag{1}$$

where δ_m is the maximum roof displacement and H is the height of the building. The parameter D_{rm} is a key factor in the shift of the basis for seismic design from strength to drift.[3] As is discussed later, maximum roof drift ratio is also of relevant importance for evaluating the damage parameter used in this study.

Considering a regular building with n floors and constant interstorey height, h, the following expression can be written:

$$H = nh \tag{2}$$

Table I. Earthquake data

Earthquake	Record	Comp.	Abbr.	Soil type	Epicen. Dist. (km)	Ms	MMI	A_{max} (g)
California 18-V-1940	El Centro	N00W	CEN	Stiff soil	11	7·0	VII–VIII	0·35
Peru 3-X-1974	Las Gardenias Lima	T	LM	Stiff soil	80	7·3	VI–VII	0·21
Rumania 4-III-1977	Bucharest	N-S	BUC	Soft soil	170	7·1	VIII	0·20
Miyagi Ken-Oki Japan 12-VII-1978	Tohoku, Senday	N00S	MY	Alluvium	100	7·4	VII–VIII	0·26
Chile 3-III-1985	Llolleo	N10E	LLO	Stiff soil	45	7·8	VIII	0·67
	Viña Del Mar	S20W	VM	Sandstone	84	7·8	VI–VII	0·36
Mexico 19-IX-1985	SCT	E00W	SCT	Lacustrine clay	400	8·1	VIII–IX	0·17
	Viveros	N00E	VI	Transition	400	8·1	V–VI	0·045
	La Union	S00E	UN	Stiff soil	100	8·1	V–VI	0·17
San Salvador 10-X-1986	CIG	E00W	SS	Stiff soil	9	5·4	VIII–IX	0·69
Mexico 25-IV-1989	Roma	N22W	RM	Lacustrine clay	400	6·9	V–VI	0·036
Loma Prieta 17-X-1989	Oakland Harbor	305°	OK	Soft soil (mud bay)	90	7·1	VI–VII	0·27
Northridge 17-I-1994	Sylmar	360°	SYL	Stiff soil	15	6·8	VIII–IX	0·84
	Santa Monica	90°	SM	Soft soil	24	6·8	VIII–IX	0·88
Hyogoken-Nanbu Japan 17-I-1995	Kobe JMA	NOOE	KOB	Alluvium	10	6·9	VIII–IX	0·84

In addition, the fundamental period of a building, T^*, and n can be related by

$$T^* = n/\lambda \tag{3}$$

The parameter λ, which generally depends on the type of structural system, is later commented in the paper.

The seismic response of the building is related here to the response of a SDOF system with a lateral displacement u and a yielding displacement u_y. A basic assumption in this procedure is that the fundamental circular frequency, ω^*, and the maximum global displacement ductility ratio, μ_m, in the multistorey building are equal to the circular frequency and maximum displacement ductility ratio of the SDOF system, respectively. With this assumption, δ_m and u_y can be related by means of the parameter γ using the following expression:

$$\gamma = \delta_m/\mu_m u_y \tag{4}$$

For most cases of regular frame buildings, a conservative estimation for γ is the value 1·5.[2,3] A similar value has been suggested for structural wall buildings.[4]

Combining equations (1)–(4), equation (1) can be rewritten as

$$D_{rm} = \mu_m \gamma u_y/T^* \lambda h \tag{5}$$

In general λ depends on the type of structural system. Measured building periods from small amplitude vibration tests suggest some typical values for λ. In the case of structural wall buildings as those designed according to Chilean practice before 1985, a good estimate of λ is 20.[4] A comparison of measured periods for small amplitude vibration tests of typical Japanese buildings constructed before the Miyagiken-Oki earthquake,[5] with results obtained using equation (3) for a λ value of 20, suggests a reasonable agreement. For frame or frame-wall buildings designed according to US practice, a λ value equal to 10 is commonly used.[6] A similar value for λ has been suggested for typical RC buildings that were constructed before 1985 in Mexico City on firm soil.[7] Lower values for λ should be used for RC buildings in the lake bed area of Mexico City, which is mainly caused by base rotation due to soil flexibility. Some analyses of seismic response of fixed-base and soil–structure-interaction (SSI) systems have shown that soil flexibility does not cause important changes either on hysteretic energy demands in structures[8] or on lateral displacements relative to the ground.[9] According to these analyses a reasonable estimation for the seismic response of a SSI system on soft soil in Mexico City can be obtained using seismic response results of the fixed-base system and the corresponding SSI period. A value of about 1·3 T^* has been suggested for evaluating the SSI period,[9] where T^* is evaluated considering the fixed-base case.

It is mentioned in the literature that a reduction in lateral stiffness should be considered when analysing the response of buildings during earthquakes.[6] It has also been found that even with no visible structural damage, periods of vibration obtained from earthquake records are significantly longer than those measured from small amplitude vibration tests.[10] Thus, as an approximate procedure, it is assumed in this study that the effective fundamental period of a building is equal to $\sqrt{2}$ times the fundamental period of vibration obtained from small amplitude vibration tests, which considers a reduction in lateral stiffness during earthquakes of 50%. Thus, when evaluating D_{rm}, the previously discussed λ values should be affected by the factor $(\sqrt{2})^{-1}$.

Based on the reported values of λ and on a review of typical building construction practice in the countries where the records used here were obtained, two groups of structures were considered: (1) structural wall buildings, and (2) frame and dual systems. In addition, structural wall

buildings were considered representative of building construction practice in Peru, Chile and Japan. For other countries, frame and dual systems were considered representative of their building construction practice.

For each earthquake analysed h was assumed constant and equal to 2·7 m. Considering the previous discussion for defining the effective fundamental period of a building in the fixed-base case, λ was taken equal to 14·1 for structural wall buildings and 7·1 for frame and dual systems. In all cases γ was taken equal to 1·5. The evaluation of D_{rm} for a SSI system on soft soil in Mexico City was performed using D_{rm} spectra for the fixed-base system and the SSI period, which in this study is evaluated as 1·3 T^*.

Figure 1 shows plots of D_{rm} spectra for given ductility displacement ratios, μ (1, 2, 4, 8) and considering a fraction of critical damping, ξ, equal to 0·05. An inspection of inelastic results shows that in general the highest roof drift ratios correspond to frame systems responding to the SCT and SYL records. They also show that for the SCT record, inelastic D_{rm} demands in the period range of about 1·5–3 s are almost independent of the levels of μ values.

Although D_{rm} cannot give information on the distribution of damage within a structure, it can be a valuable tool for performing a quick and simple evaluation of building performance. In the following, D_{rm} values associated with acceptable levels of building performance are discussed.

For code-designed RC frames, it has been found that they will have an acceptable level of seismic performance if interstorey drift ratios are kept below the value 0·02.[2] This limit might be low, if a high level of building damage without structural failure is expected during a strong earthquake. Although the ratio between maximum interstorey and roof drift ratios depends on structural and earthquake characteristics, for some typical regular RC frames a value of 2 may be considered representative of this ratio.[11] Therefore, for these cases, a maximum interstorey drift ratio equal to 0·02 would correspond to a roof drift ratio equal to 0·01. As for structural wall buildings, an acceptable building performance with low or moderate structural damage has been associated with roof drift ratios up to 0·01.[12] It is of interest to notice that the common definition of interstorey drift (the difference in lateral displacements for two adjacent floors divided by the distance between the floors) is irrelevant for a flexural wall, except at the base of the building.[4,5] For a wall building, the use of the interstorey distortion would be more appropiate.[4,5,11] It has been shown that when considering the actual mode shape of a prismatic wall, the interstorey distortion varies from $1{\cdot}38D_{rm}$ at the fixed base to zero at the top of the building.[4]

The values discussed above for interstorey drift ratios in RC frames and interstorey distortion in wall buildings help to explain why the NEHRP guidelines for seismic rehabilitation of buildings, FEMA-273 1997,[13] suggest that for the same performance level, the interstorey drift ratio for RC frames is twice as much as that for wall buildings.

Based on the above discussion, in this study it is considered that an acceptable performance level of typical regular RC frames and structural wall buildings during earthquakes is associated with values of D_{rm} up to 0·01.

Figure 1 shows that the records with D_{rm} demands higher than 0·01 in a wide range of periods were SCT, SYL, BUC, KOB, SS and OK. As reported in the literature,[14–18] the earthquakes corresponding to these records are associated with considerable seismic damage in structures, which demonstrates the good correlation between displacement demands and seismic damage. Figure 1 also shows that in a wide range of periods D_{rm} demands for the LLO and VM records are

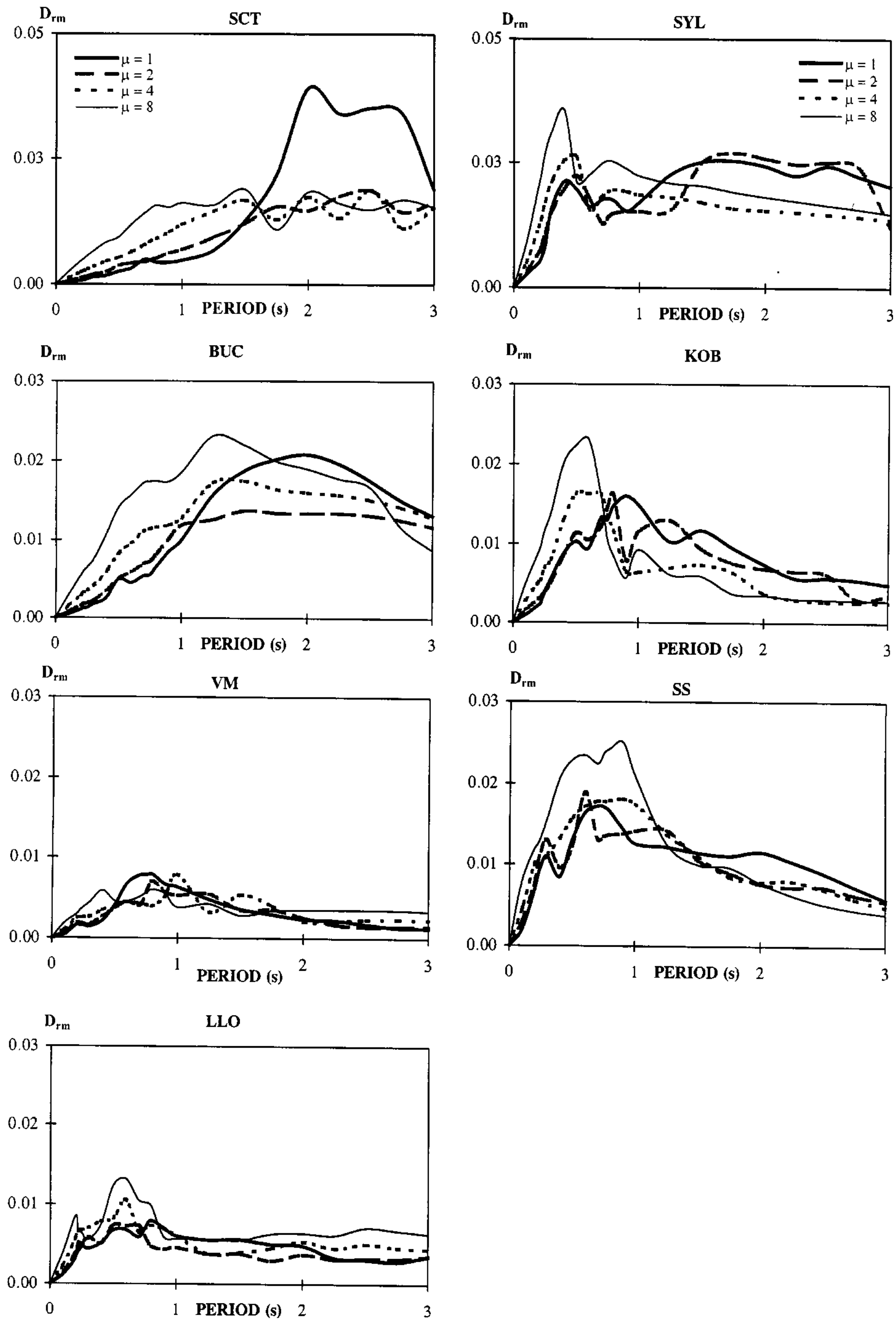

Figure 1. D_{rm} spectra for 15 earthquake ground motion records

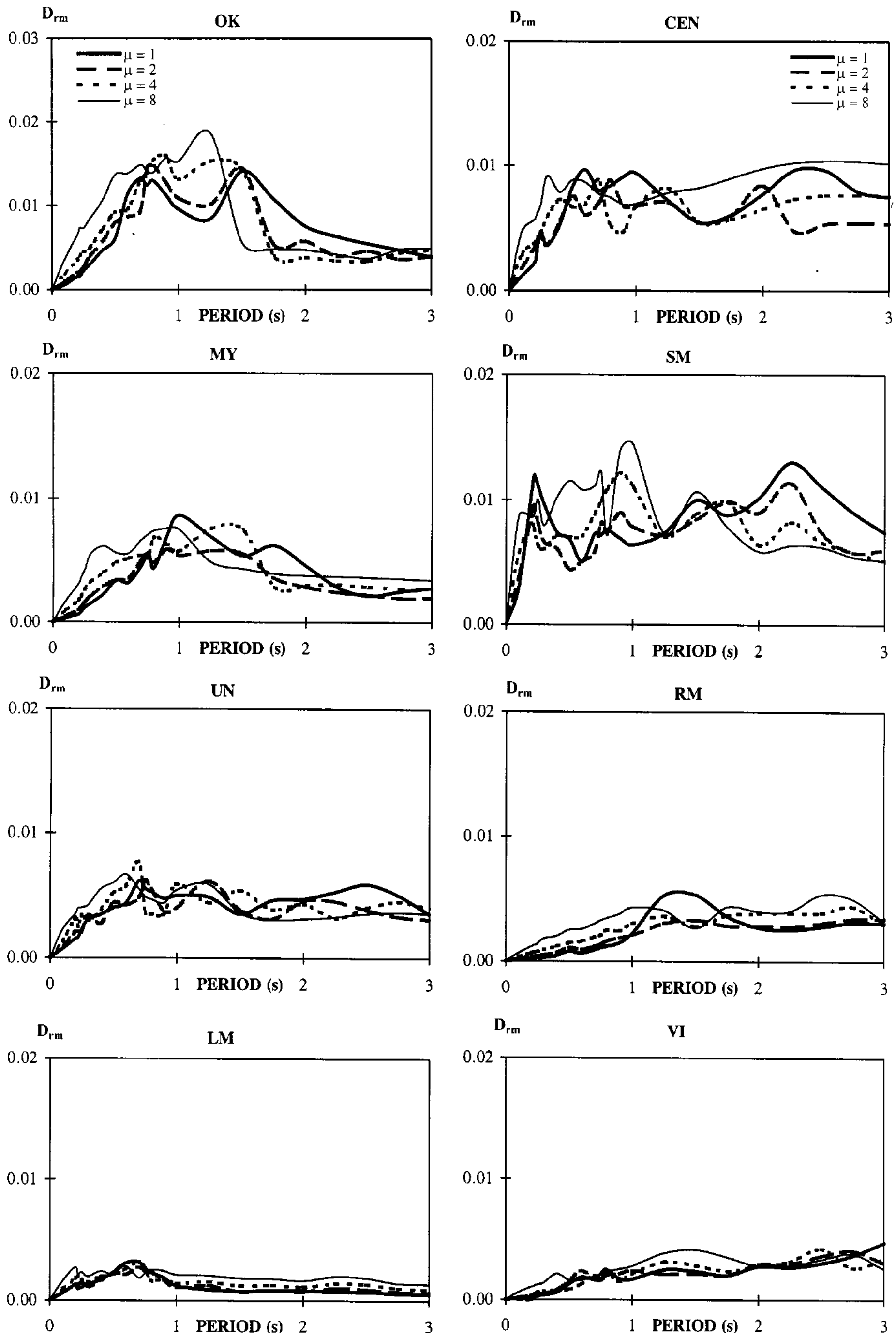

Figure 1. (*Continued*)

lower than 0·01, which is in agreement with the low rate of damage or collapses of buildings observed in the 1985 Chile earthquake. These results show the importance of using structural wall buildings for reducing displacement demands and consequently to reduce seismic damage.

Other results that confirm the good correlation between displacement demands and seismic damage are also shown in Figure 1. These are the cases of the very small D_{rm} demands corresponding to the RM, LM and VI records, which are in reasonable agreement with the scarce damage observed in the earthquakes associated to these records. Although the VI record and the well known SCT record were obtained in the same earthquake in Mexico City, the stations corresponding to these records were located on different types of soil. The large building damage corresponding to the SCT record, as compared to the VI record, points out the importance of seismic zonation when analysing the response of structures. In the case of the RM and SCT records, they were both recorded on the same type of soil in Mexico City in the earthquakes of 1989 and 1985, respectively. However, the RM record corresponds to an earthquake with a lower Mercalli intensity as compared to that of the SCT record, see Table I.

Caution should be taken when using results of Figure 1 for analysing lateral displacements of irregular structures, such as for instance those of the soft storey type. Uang and Bertero[19] have shown that in the case of a building with n floors having a soft storey in the first level, interstorey drift in this level might reach the value nD_{rm}, which might explain the high rate of severe damage or collapses of this type of structures during past earthquakes.

EVALUATION OF INELASTIC BEHAVIOUR OF SDOF STRUCTURES AND OBSERVED DAMAGE IN EARTHQUAKES

Seismic resistance

By specifying a displacement ductility ratio, μ, for an elastoplastic SDOF system for a given earthquake record, the seismic resistance, C_y, is defined as

$$C_y = R_y/Mg \tag{6}$$

where R_y is the yielding resistance and M the mass of the structure.

An evaluation of C_y spectra for the previously mentioned set of 15 accelerograms has been performed by Rodriguez and Aristizabal.[20] These spectra were obtained for various displacement ratios, μ, and considering ξ equal to 0·05. According to this evaluation the highest resistance demand corresponds to the SM record, followed in decreasing order by the SYL, KOB, LLO, SS, VM, SCT, and other records.

The seismic resistance response spectra is a basic tool in a typical seismic design process. It has also been used for explaining the response of buildings during earthquakes as well as for assessing the seismic vulnerability of existing structures. It is of interest to evaluate the soundness of using C_y as a measure of seismic damage. In the case of the 1985 Mexico City earthquake, when considering inelastic response for the SCT record, the distribution of building damage observed in this earthquake has a poor correlation with the demands of the SCT seismic resistance spectra,[7] which questions the use of C_y as a measure of seismic damage.

PROPOSED PARAMETER FOR MEASURING SEISMIC DAMAGE

The reader is referred elsewhere[7] for a detailed description of the method of analysis and of the hypotheses assumed for deriving the proposed parameter, I_D, which is defined as follows:

$$I_D = \frac{\gamma^2 E_{\mathrm{H}}}{(\omega^* H D_{\mathrm{rd}})^2} \tag{7}$$

where E_{H} is the total hysteretic energy per unit mass dissipated by a SDOF system during an earthquake, and D_{rd} is the maximum roof drift ratio in a building associated to an acceptable building performance in a strong earthquake. As stated earlier, a value of 0·01 can be assumed for D_{rd}.

It has been shown[7] that the numerator in equation (7) represents the hysteretic energy dissipated by a multistorey structure responding to an earthquake, and the denominator represents an elastic energy absorbed in a full cycle by an elastic model of the multistorey structure (when it is forced to displace to its extreme overall drift $+D_{\mathrm{rd}}$ and $-D_{\mathrm{rd}}$)

Considering the definition $\omega^* = 2\pi/T^*$ and substituting equations (2) and (3) in equation (7) yields

$$I_D = \frac{\gamma^2 E_{\mathrm{H}}}{(2\pi\lambda h D_{\mathrm{rd}})^2} \tag{8}$$

It should be pointed out that the difference between the hysteretic energy E_{H} and the damage parameter I_D is not only a matter of a number of constants, as might be suggested by equation (8), but a consequence of a fundamental concept involved in the definition of I_D. According to this concept, the potential structural damage during an earthquake is related not only to the expected hysteretic energy dissipated by a structure, but also to the type of structural system as well as to the overall drift that may be considered acceptable for the structure. Some implications of this concept are discussed next. For the sake of comparison let us consider a structural wall system and a frame or dual system, and a λ value for the former which doubles those of the latter systems. In addition, let us assume that γ, h, and D_{rd} are constants, and that the corresponding values of T^* and μ_{m} in both systems are equal. With these assumptions and according to equation (8), when analyzing a specific earthquake record, the I_D value corresponding to the frame or dual systems would be four times that corresponding to the wall system, which shows the importance of the type of structural system for reducing seismic damage.

Evaluation of I_D

The selected earthquake ground motions were evaluated using the parameter I_D defined in equation (8). The assumed values for the parameters γ, λ and h were those used for the previous discussed evaluation of D_{rm}. In addition, D_{rd} was assumed equal to 0·01. Plots of numerical values of I_D as a function of fundamental period are shown in Figure 2 for given displacement ductility ratios, and considering ξ equal to 0·05. The highest seismic damage parameter corresponds to the SCT record (Mexico City, 1985), followed in decreasing order by SYL (Northridge, USA, 1994), BUC (Rumania, 1977), KOB (Kobe, Japan, 1995), VM (Viña del Mar, Chile, 1985), SS (San Salvador, 1986), LLO (Llolleo, Chile, 1985), OK (Loma Prieta, 1989), CEN (California, 1940), and others. The results also show that the earthquakes with lowest damage parameter where those

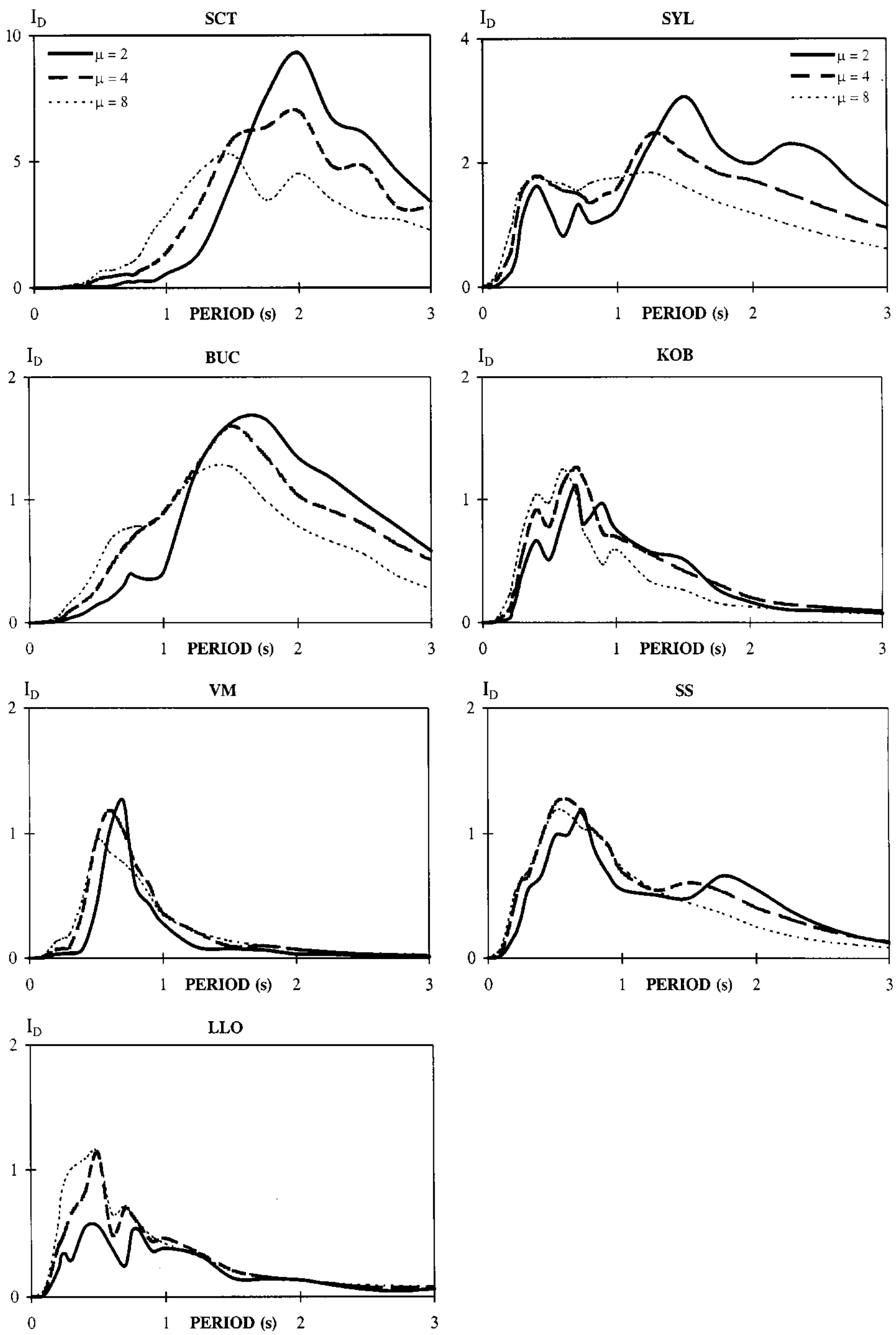

Figure 2. Measure of seismic damage for 15 earthquake ground motion records

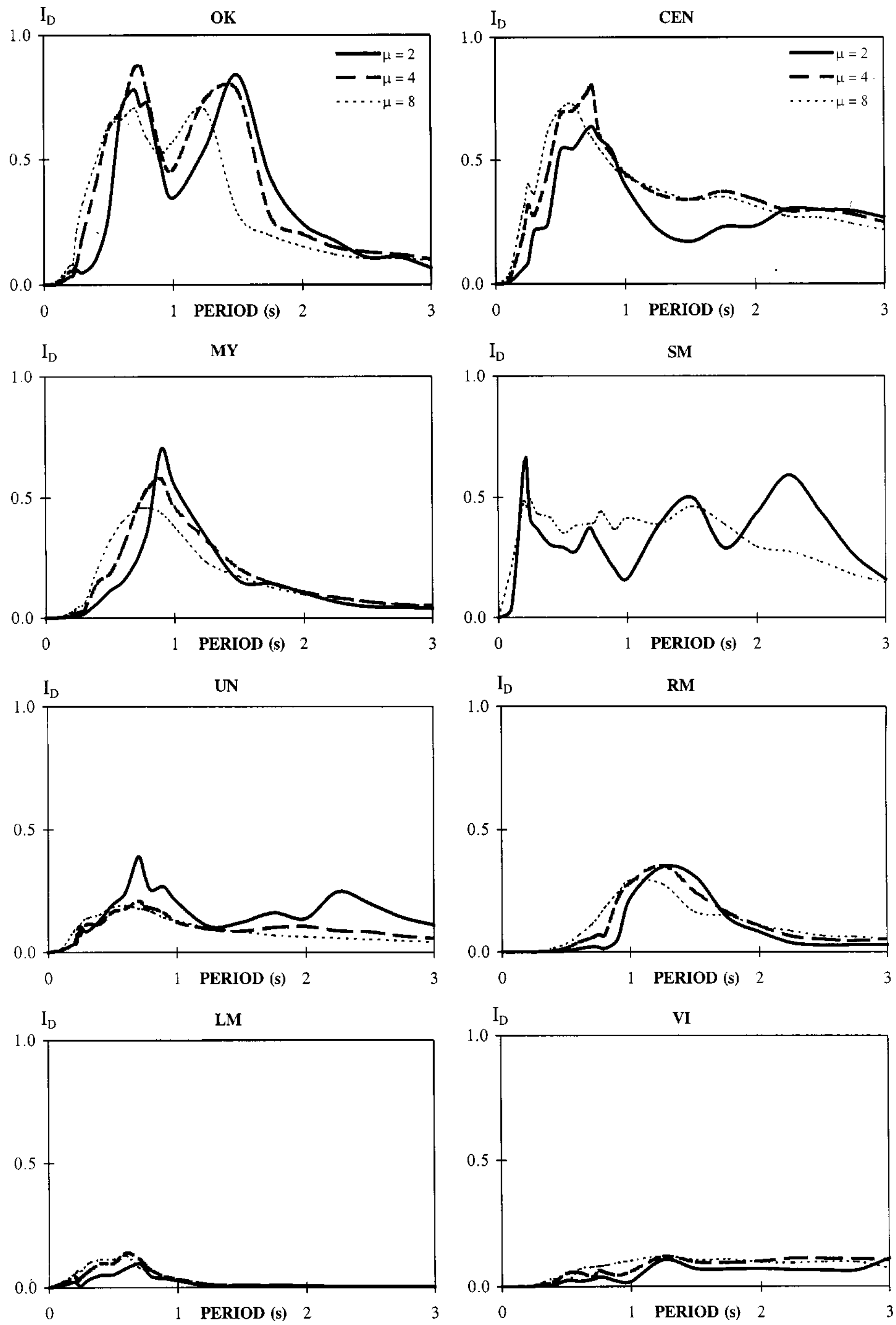

Figure 2. (*Continued*)

related to the following records: RM (Mexico City, 1989), LM (Lima, Peru, 1974), and VI (Mexico City, 1985). Results show in general an acceptable correlation between I_D and global building damage observed during the earthquakes studied. It is interesting to notice that the CEN record has a calculated damage parameter that is lower than several other ones. However, this record has been considered for many years representative of an intense earthquake.

It has been shown that plots of I_D as a function of fundamental period and the corresponding hysteretic energy spectra have similar shapes.[7] It is of interest to compare this shape and the distribution of building damage as a function of fundamental period, especially in the cases of the SCT and VM records, where predominant periods are associated with higher I_D values (Figure 2). In the 1985 Mexico City earthquake, most building damage and collapses were observed in the range of 6–15 floors,[7] which according to the previous discussion for estimating effective periods considering SSI would correspond to the range of 1·1–2·7 s. This period range has a good correlation with the distribution of maximum I_D values for the SCT record shown in Figure 2. During the 1985 Chile earthquake, buildings in Viña del Mar showed higher damage in the range 8–15 floors,[12] which would correspond to a period range of 0·6–1·1 s. This period range is in reasonable agreement with the distribution of maximum I_D values for the VM record shown in Figure 2.

Results shown in Figure 2 indicate that damage in some cases increases and in other cases decreases with increased ductility. For instance, for the SCT record, Figure 2 shows that for structures in the period range less than about 1·5 s, the higher the ductility, the greater the damage that might be expected in the structure. On the contrary, for structures in the period range larger than about 1·5 s, the higher the ductility, the smaller the damage that might be expected in the structure. Such behaviour for the SCT case has been explained by analysing the corresponding values of R_y, u_y and the cumulative ductility for SDOF systems with different ductility levels.[21] It has been found that large inelastic excursions for ductile structures in the period range less than about 1·5 s lead to high E_H values, since strength in this period range is only moderately influenced by a change in the ductility level. On the contrary, for records on stiff soils such as CEN (El Centro), LLO (Chile,1985) and SYL (Northridge, 1994) in most cases strength is strongly influenced by a change in the ductility level. As a result, low ductility levels are associated with high strength demands in a structure, with fewer incursions in the inelastic range and lower demands of hysteretic energy as compared to those corresponding to more ductile structures, in which lower strength demands are associated with several incursions in the inelastic range and higher hysteretic energy demands.

It is of interest to discuss another form of equation (8) that was proposed in the original derivation of the parameter I_D. The alternative expression for I_D is defined as:[7]

$$I_D = N_e \left(\frac{D_{rm}}{D_{rd}}\right)^2 \tag{9}$$

where N_e is given by

$$N_e = \frac{E_H}{(\mu_m \omega^* u_y)^2} \tag{10}$$

The parameter N_e is a normalized hysteretic energy; $\sqrt{N_e}$ has been used by Fajfar[22] for a seismic design procedure considering the effect of cumulative seismic damage. According to Fajfar,[22] $\sqrt{N_e}$ is a relatively stable parameter. It follows that the ratio D_{rm}/D_{rd} is of relevant

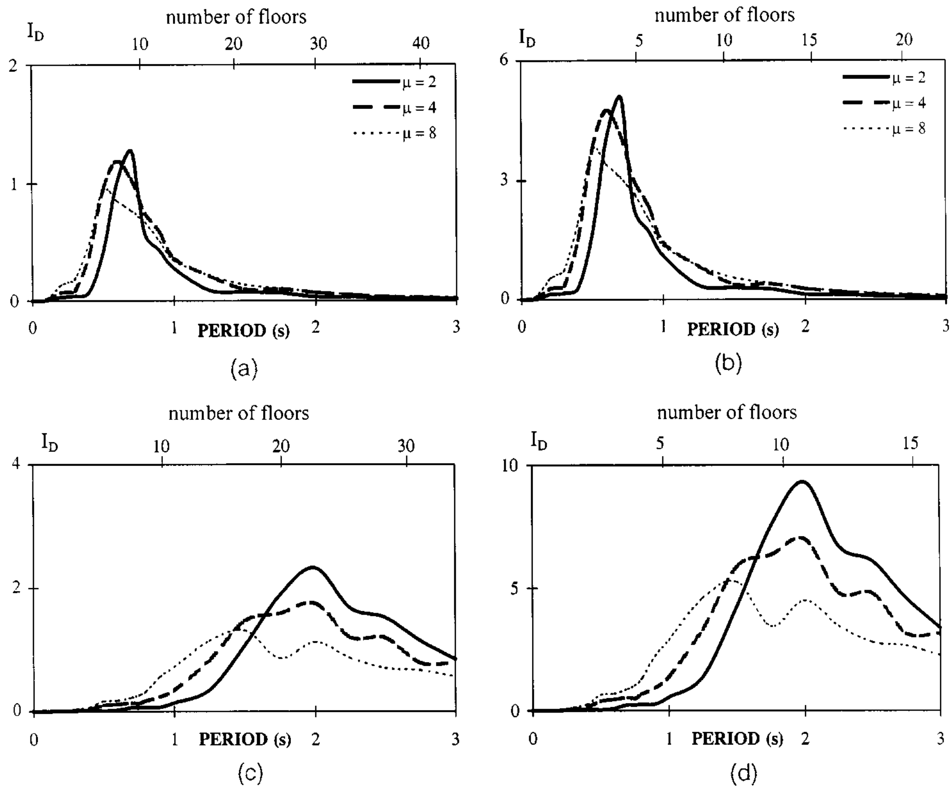

Figure 3. Measure of seismic damage for the 1985 Chile and Mexico earthquakes: (a) VM record and structural wall buildings; (b) VM record and frame buildings; (c) SCT record and structural wall buildings; (d) SCT record and frame buildings

importance for evaluating the proposed parameter I_D. If $D_{\rm rd}$ is assumed constant, the above finding and equation (9) indicate that I_D would be directly proportional to $D_{\rm rm}$ squared, which suggests the importance of controlling displacements for minimizing seismic damage.

Although the results shown in Figure 2 allow to perform a comparison between predicted and observed response of typical structural systems during the earthquakes studied, it is also of interest to analyse the expected seismic behaviour of structural systems that were not typical of the sites where those earthquakes occurred. Such an analysis can be done based on the results shown in Figure 3, which in addition to the results discussed before for typical existing buildings during the 1985 Mexico City and 1985 Chile earthquakes, it now includes results for the cases of wall buildings during the 1985 Mexico City earthquake (SCT record) and frame buildings during the 1985 Chile earthquake (VM record). Figure 3 shows plots of I_D as a function of fundamental period, for given displacement ductility ratios, and considering ξ equal to 0·05; values for the other parameters involved in the evaluation of I_D were those discussed previously. Since the same building height should be considered for a fair comparison of the seismic behaviour of frame and wall buildings (which according to our previous discussion would lead to a longer fundamental period for a frame building than that for a wall building), Figure 3 also shows at the top the

number of floors, n, that corresponds to the given scale of fundamental periods. The fundamental period, T^*, for buildings in Viña del Mar is evaluated as $n/7{\cdot}1$ for frame buildings and $n/14{\cdot}1$ for wall buildings. For buildings in Mexico City, the effective SSI period to be used with spectra for the fixed-base system is assumed to be equal to $1{\cdot}3\ T^*$.

According to predicted seismic response of buildings in Viña del Mar, see Figures 3(a) and (b), frame buildings with less than about 10 storeys have a greater damage than wall buildings with the same height. Notice that in the case of buildings with about five storeys there is a significant difference in the seismic damage between frame and wall buildings. For five-storey frame buildings I_D values are at least ten times those of wall buildings. On the contrary, wall buildings with more than 10 storeys may have a higher seismic damage than frame buildings with the same height. However, in these cases, the levels of expected seismic damage in both structural systems are much lower than those corresponding to frame buildings in the range of about five storeys. The importance of using wall buildings for reducing seismic damage is especially evident in the case of buildings in Mexico City. Figures 3(c) and 3(d) show that the seismic damage of frame buildings with about 15 storeys or less is much greater than that of wall buildings of the same height.

An additional comment on I_D is that it can be considered an approximate measure of the global structural response for regular multistorey buildings, and can be used as a tool for performing a quick and simple seismic damage assessment for this type of buildings. In irregular multistorey buildings, damage can be concentrated in one storey, or the hypothesis of a constant deflected shape might not be consistent with actual deflected shapes of a building during vibration, which suggests that for irregular buildings caution should be taken when evaluating I_D.

CONCLUSIONS

A parameter previously developed by the first author is used in this study for performing an evaluation of seismic damage using data from 11 earthquakes experienced in several countries. Results from the evaluation show an acceptable correlation with global damage observed during the earthquakes studied. Results found in this study also indicate the importance of controlling lateral displacements, mainly roof drift ratio in regular multistorey buildings, for minimizing seismic damage.

It is generally accepted that seismic damage analysis should involve non-linear response. This concept, as well as the acceptable agreement found between results using I_D and observed earthquake damage, suggest that this parameter can be used as a basic tool for developing a rational seismic design approach and for evaluating expected seismic performance of existing regular structures.

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REFERENCES

1. M. Saiidi and M. Sozen, 'Simple nonlinear analysis of RC structures', *J. Struct. Div. ASCE*, **107**, 937–952 (1981).
2. X. Qi and J. Moehle, 'Displacement design approach for reinforced concrete structures subjected to earthquakes', *Report No. UCB/EERC-91/02*, Earthquake Engineering Research Center, Univ. California, Berkeley, 1991.
3. M. Sozen, 'Drift-driven design for earthquake resistance of reinforced concrete', EERC-CUREe Symposium in Honor of Vitelmo Bertero, *Report UCB/EERC-97/05*, EERC, Univ. California, Berkeley, 1997.
4. R. Riddell and J. Vasquez, 'Shear wall buildings: a type of construction less vulnerable to earthquakes?', *Proc. Int. Symp. Earthquake Disaster Prevention*, Vol. III, Mexico City, 1992, pp. 37–51.
5. B. B. Algan, 'Drift and damage considerations in earthquake-resistant design of reinforced concrete buildings', *Ph.D. Thesis*, Graduate College of the Univ. Illinois, Urbana-Champain, USA, 1982.
6. J. Wallace and J. Moehle, 'Ductility and detailing requirements of bearing wall buildings', *J. Struct. Div. ASCE*, **118**, 1625–1644 (1992).
7. M. Rodriguez, 'A Measure of the capacity of earthquake ground motions to damage structures', *Earthquake Engng. Struct. Dyn.* **23**(6), 627–643 (1994).
8. J. Bielak, E. Bazan and B. L. Doo, 'Earthquake response of simple degrading structures supported on flexible soils', *Proc. 9th World Conf. on Earthquake Engng.*, Vol. V, Tokyo, Japan, 1988, pp. 135–140.
9. E. Bazan, I. Diaz-Molina, J. Bielak and N. Bazan, 'Probabilistic seismic response of inelastic building foundation systems', *Proc. 10th World Conf. on Earthquake Engng.*, Madrid, Spain, Vol. 3, 1992, pp. 1559–1565.
10. J. C. Anderson, E. Miranda, V. V. Bertero and The Kajima Project Research Team, 'Evaluation of the seismic performance of a thirty-storey RC building', *Report No. UCB/EERC-91/16, EERC*, College of Engineering, Univ. California, Berkeley, 1991.
11. J. Moehle, 'Displacement-based design of RC structures subjected to earthquakes', *Earthquake Spectra*, **8**, 403–428 (1992).
12. S. Wood, 'Performance of reinforced concrete buildings during the 1985 Chile earthquake. Implications for the design of structural walls', *J. Earthquake Spectra*, **7**, 607–637 (1991).
13. FEMA-273, NERHP Guidelines for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency, *Report No. FEMA-273*, 1997.
14. EERI, 'The San Salvador earthquake of October 10, 1986', *J. Earthquake Spectra*, **3**(3), 465–481 (1987).
15. EERI, 'Loma Prieta earthquake reconnoissance report', *J. Earthquake Spectra*, **6** (suppl.) (1990).
16. EERI, 'Northridge Earthquake January 17, 1994, 'Preliminary reconnoissance report', Earthquake Engineering Research Institute, Publication No 94-01 (1994).
17. EERI, 'The Hyogo-ken Nambu earthquake January 17, 1995, 'Preliminary Reconnoissance Report', Earthquake Engineering Research Institute, Publication No 95-04 (1995).
18. M. Fintel, 'Performance of buildings with shear walls in earthquakes of the last thirty years', *PCI J.*, **140**(3), 62–80 (1995).
19. C. M. Uang and V. Bertero, 'Implications of recorded earthquake ground motions on seismic design of building structures', *Report No. UCB/EERC-88/13*, EERC, Univ. California, Berkeley, 1988.
20. M. Rodriguez and J. C. Aristizabal, 'Evaluación de la capacidad destructiva de terremotos', Report Instituto de Ingenieria, N°609, UNAM, 1998, (in Spanish).
21. M. Rodriguez, 'Evaluation of seismic performance of buildings using a damage analysis approach', *Proc. 11th Eur. Conf. Earthquake Engng.*, Paris, 1998.
22. P. Fajfar, 'Equivalent ductility factor, taking into account low-cycle fatigue', *Earthquake Engng. Struct. Dyn.*, **21**, 837–848 (1992).